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SEASONAL, LATITUDINAL, AND SECULAR VARIATIONS IN TEMPERATURE TREND: EVIDENCE FOR INFLUENCE OF ANTHROPOGENIC SULFATE

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Abstract. Tropospheric aerosols increase the shortwave reflectivity of the Earth-atmosphere system both by scattering light directly, in the absence of clouds, and by enhancing cloud reflectivity. The radiative forcing of climate exerted by anthropogenic sulfate aerosols, derived mainly from SO_2 emitted from fossil fuel combustion, is opposite that due to anthropogenic greenhouse gases and is estimated to be of comparable average magnitude in Northern Hemisphere midlatitudes. However, persuasive evidence of climate response to this forcing has thus far been lacking. Here we examine patterns of seasonal and latitudinal variations in temperature anomaly trend for evidence of such a response. Pronounced minima in the rate of temperature increase in summer months in Northern Hemisphere midlatitudes are consistent with the latitudinal distribution of anthropogenic sulfate and changes in the rate of SO_2 emissions over the industrial era.

Introduction

Tropospheric aerosol sulfate is derived mainly from biogenic sulfur-containing gases (mostly dimethylsulfide) and SO_2 emitted principally from fossil fuel combustion. SO_2 emissions have increased substantially over the past 150 years and now considerably exceed estimated natural emissions of gaseous precursors of sulfate aerosol (Figure 1). The resultant increase in sulfate aerosol concentration is thought to have exerted a change in Earth's shortwave radiation budget that is substantial in the context of longwave forcing by the increase in greenhouse gases over the same period [Charlson et al., 1992; Wigley and Raper, 1992].

More than 90% of anthropogenic SO_2 introduced into the atmosphere is emitted in the Northern Hemisphere (NH), and approximately 70% between 30°N and 60°N [Spiro et al., 1992; Dignon, 1992]. Model calculations indicate that both the resulting sulfate aerosol [Charlson et al., 1991; Langner and Rodhe, 1991] and radiative forcing [Charlson et al., 1991; Kiehl and Briegleb, 1993] are confined primarily to 30-60°N, in agreement with observed sulfate aerosol concentrations [Schwartz, 1988] and satellite observations of clear-sky [Durkee et al., 1991] and cloud [Han et al., 1993] albedo. However there is scant evidence of the influence of this radiative forcing in interhemispheric differences of annual temperature anomaly trend over the industrial era [Schwartz, 1988; Wigley, 1989]. On the other hand, comparison of trends of mean daily maximum (mostly daytime) and minimum (mostly nighttime) temperatures in industrial regions [Karl et al., 1991] indicates a greater rate of warming at night than during daytime, perhaps indicative of a shortwave forcing by anthropogenic sulfate aerosol in conjunction with overall global warming over this period.

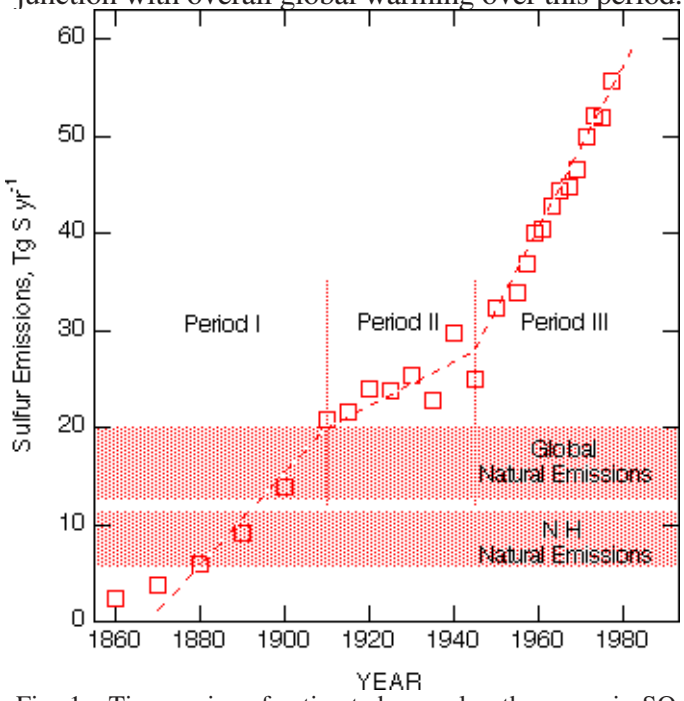

Fig. 1. Time series of estimated annual anthropogenic SO_2 emissions in midlatitudes (30-60°) of the Northern Hemisphere. Midlatitude NH emissions are calculated from estimated global emissions [Möller, 1984] as 98% of global emissions until 1910, 90% in 1945, and 70% in 1986 [Dignon and Hameed, 1989; Spiro et al., 1992] with linear interpolation in periods II and III. Other estimates, e.g., Robinson and Robbins [1971], are similar. Dashed lines represent rate of increase of 0.50, 0.23, and 0.84 Tg S yr^{-1} for periods I, II, and III, respectively, although such a rate of increase for period III was probably not sustained in the 1980s [Spiro et al., 1992]. Also shown are estimates of total global and NH natural emissions of gaseous reduced sulfur compounds and sulfur dioxide [Bates et al., 1992]; the widths of the bands represent ranges of estimates.

Because of greater insolation in summer than winter, the shortwave radiative influence of anthropogenic sulfate aerosol is expected to be greater in summer, and this might lead to a lesser rate of warming in NH midlatitudes (30° to 60°) in summer than in winter that would serve as a sensitive indicator of climate response to sulfate aerosol forcing. To examine the seasonal dependence of the forcing we carried out a radiative transfer model calculation for a spatially and temporally uniform incremental aerosol optical depth of 0.04, corresponding to the difference between a background aerosol optical depth of 0.05 [Forgan, 1987] and that characteristic of industrial latitudes, 0.09. The forcing was computed for a horizontally homogeneous, cloud-free Earth at 0.55 μm using the doubling and adding code of Hansen and Travis [1974]. For this calculation the model atmosphere was divided into three layers: top layer, gaseous absorption and Rayleigh scattering ($\tau_{abs} = 0.03$, $\tau_{Ray} = 0.1$); aerosol layer, having log-normal particle size distribution with geometric mean radius 0.0285 μm, geometric standard deviation 2.239, and refractive index 1.43; Lambertian surface layer with albedo 0.15. The calculated forcing in midlatitudes is considerably greater (negative) in summer than winter (Figure 2a). Kiehl and Briegleb [1993] similarly note a greater forcing in summer than winter in industrial regions, despite similar modeled sulfate column burdens, which they likewise attribute to greater summertime insolation.

The summer-winter difference in forcing would be enhanced by higher summertime sulfate concentrations that might result from a greater summertime rate of conversion of SO_2 to sulfate [NAPAP, 1990]. Higher surface concentrations of aerosol sulfate in summer than winter (by factors of 2 to 5) are noted in eastern North America [Husain and Dutkiewicz, 1990], although not in Europe [Schaug et al., 1989]. The summer-winter difference in forcing might be enhanced also by a greater rate of new particle production in summertime and resultant increased cloud reflectivity, as might be expected from the dominance of gas-phase oxidation of SO_2 by OH in summer, versus dominance of aqueous-phase oxidation in winter [Langner et al., 1992].

It has been noted previously that the summertime rate of warming in the NH over the industrial period as a whole (1854-1986) has been considerably less than the annual mean [Gordon, 1992], with the lesser rate of summertime warming confined mainly to midlatitudes [Schönwiese and Stähler, 1991]. In

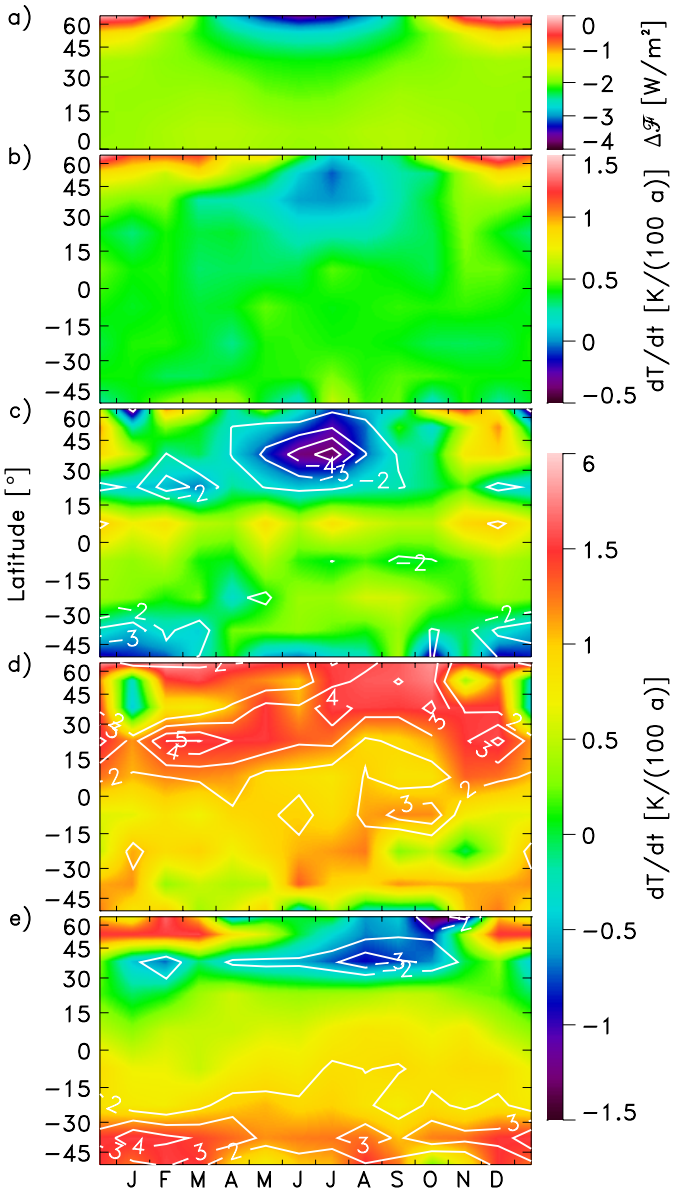

Fig. 2. Latitudinal and seasonal dependence of aerosol forcing and temperature anomaly trend. (a) Diurnal-average shortwave radiative forcing due to a uniform incremental aerosol optical depth of 0.04 (i.e., optical depth 0.09 versus optical depth 0.05) as a function of month of year and latitude for the NH only. (b) Dependence of temperature anomaly trend on month of year and latitude for the period 1854-1989 evaluated from the combined land and sea-surface temperature anomaly data set of Jones et al. [1986a] as obtained from NCAR [1990]; the figure presents a bilinear interpolation of the slopes calculated for 15° zonal area-weighted means of the original 5° by 5° gridded monthly-mean temperature anomaly data set. (c, d, e) Same as (b) but for the periods 1854-1910, 1910-1945, and 1945-1989, respectively. Note compressed color scale at high NH latitudes in winter. Labeled contours represent ratio of the difference between the temperature trend during the indicated period and that for the overall period 1854-1989 to the estimated resultant 1-σ standard error of that difference. Latitude is displayed on a sine scale in all panels.

contrast the SH exhibits little seasonal variation in warming rate over this period. These observations may be indicative of an increase in seasonal variation in forcing resulting from an increase in anthropogenic sulfate aerosol in NH midlatitudes. Wigley et al. [1992] have noted a summertime cooling trend subsequent to 1950 in regions influenced by anthropogenic aerosols relative to other regions. Recently Engardt and Rodhe [1993] have examined temperature trends between the periods 1926-45 and 1971-90 for locations which exhibit high sulfate column burdens in the Langner et al. model calculations, finding indication of summertime cooling in regions of high burden, albeit not statistically significant.

Results and Interpretation

Here we examine the seasonal and latitudinal dependence of temperature anomaly trend (hereinafter temperature trend) for the period 1854 to 1989, evaluated for 15° latitude zones from the monthly combined land and sea-surface temperature anomaly data set of the University of East Anglia Climatic Research Unit [Jones et al., 1986 a-c] as obtained from the National Center for Atmospheric Research [NCAR, 1990]. Temperature trends were evaluated as the linear regression slope of area-weighted zonal means of the monthly-mean temperature anomalies versus time, with explicit treatment of temporal autocorrelation by the Prais-Winsten generalized least-squares approach [Johnston, 1984]. The resulting temperature trends are shown as a function of latitude and season in Figure 2b. Latitudes above 75°N and below 60°S are excluded because of the short temporal record and restricted spatial coverage. Because the spatial coverage is sparse before 1880, especially for the SH, the slopes for the SH must be viewed as fairly uncertain [Jones et al., 1986 b,c]. Despite these uncertainties a strong seasonal variation in warming rate is exhibited in mid (30-60°) and high (60-75°) latitudes of the NH over the time period as a whole that contrasts markedly with the much more uniform pattern of warming exhibited in the SH. The six monthly-mean warming rates for the 30-45° and 45-60° zones of the NH in June, July, and August are the lowest globally and are in fact near zero (range 0.12 ± 0.09 K/century to -0.07 ± 0.10 K/century, i.e., slight cooling; the uncertainties are the 1-σ standard errors). The coincidence of this minimum warming rate with the latitude of maximum anthropogenic SO_2 emissions and sulfate concentrations and with the calculated seasonal maximum in shortwave aerosol forcing is suggestive of a seasonal component of the climate response to shortwave radiative forcing by anthropogenic sulfate aerosol.

Insight into possible alternative explanations of the seasonal and latitudinal variation in NH temperature trend may be gained from a study with a coupled ocean-atmosphere model [Manabe et al., 1992], which examined temperature trend as a function of latitude and season in response to a hemispherically symmetric forcing, corresponding to a 1% yr^{-1} increase in CO_2, roughly equal to the current rate of increase in forcing by greenhouse gases. Except for NH midlatitude summer the model results agree closely with the observed trends at all latitudes and seasons, specifically including the marked enhancement of the wintertime warming rate above 60°N. The enhanced high-latitude wintertime warming is attributed to latent heat trapped during sea ice melting in summer and released in winter through a thus thinner ice layer [Manabe et al., 1992]. However little seasonal variation was exhibited in the modeled temperature trends in the latitude range 30°N to 60°N, and in particular no lesser rate of summertime warming at these latitudes, in contrast to the observations. The observed warming rate of the 60-75°N band, while greatly elevated in wintertime, does not drop in summer more than 0.2 K/century below the hemispheric mean of 0.4 K/century, whereas that for the midlatitude bands is not greatly elevated in wintertime but is well below the hemispheric mean in summertime. The seasonal variation in the 60-75°N band thus seems largely unrelated to the observed variation in the 30-45°N and 45-60°N bands.

To further examine for evidence of influence of sulfate aerosol on temperature trends, we note that the rate of increase in anthropogenic SO_2 emissions (Figure 1) has not been constant throughout the industrial era. Prior to 1910 (period I) and between 1945 and 1989 (period III) emissions increased rapidly, initially in Europe and North America, and later in Asia. In contrast, between 1910 and 1945 (period II) the rate of increase was much lower, primarily because of large-scale conversion from coal to oil. Since sulfate aerosol is short lived in the atmosphere, a change in forcing is brought about only by a change in emissions rate. Therefore the effect of SO_2 emissions on temperature trend would be expected to be greatest in periods I and III, but minimal in period II. Consequently, we examined the

latitudinal and seasonal dependence of temperature trend separately for the three time periods (Figure 2c-e). Periods I and III exhibit temperature trends in NH midlatitudes that have seasonal and latitudinal distributions similar to that of the decreased warming rate exhibited by the period as a whole and in fact show significant cooling in summer months. The labeled contours in these figures indicate the statistical quality of the difference in temperature trend between the individual time periods and the 1854-1989 period as a whole. For periods I and III the temperature trend in NH midlatitude summer is less than that for the time period as a whole by more than three times the standard error of the difference. In contrast, during Period II the NH midlatitudes warmed at a rate comparable to that in other seasons and much greater than that for the time period as a whole, again by several times the standard error of the difference. Moreover this warming pattern agrees closely with the model results of Manabe et al. [1992]. To be sure, there is not a one-to-one correspondence between temperature trend and rate of increase in sulfur emissions; this could be due to nonlinear response to aerosol forcing or to differences in geographical distribution of emissions, and/or to influences unrelated to aerosol forcing. Nonetheless, the markedly different NH midlatitude summertime temperature trend associated with the differing rates of increase in SO_2 emissions characterizing the three time periods supports attribution of the lower warming rate in NH midlatitudes in summer to the influence of anthropogenic sulfate.

Conclusions

The seasonal variation of shortwave radiative forcing by aerosols indicated in Figure 2a suggests that examination of the spatial and temporal patterns of temperature trend should provide a powerful means of testing climate response to increased sulfate aerosol over the industrial era. The seasonal dependence of observed temperature trend in NH midlatitudes over the industrial period as a whole and in the two periods of greatly increasing SO_2 emission rates is qualitatively consistent with the historical pattern of this forcing. The seasonal variation in forcing and observed temperature trend thus suggests that response to this variation in forcing be explicitly examined in climate model studies.

Three final points should be noted. First, if the minimum in warming rate noted for midlatitude summers is due to shortwave radiative forcing by anthropogenic sulfate aerosol, then the observed seasonal and latitudinal differences in warming rate must be viewed as a substantial underestimate of the magnitude of the contribution of this forcing to global cooling, as the forcing will be active in all seasons (Figure 2a) and because a forcing in a given season and location may be expected to influence temperature in other seasons and locations. Second, to the extent longwave forcing by anthropogenic greenhouse gases has been offset by shortwave forcing by sulfate aerosols, the warming that would have occurred from the greenhouse forcing alone may be substantially greater than that which has actually occurred thus far over the industrial era. Sulfate forcing may thus account for the apparently too great response to greenhouse forcing, relative to observed trends, of climate models that do not include this forcing [Houghton et al., 1992; Wigley and Raper, 1992]. Third, improvements in description of the spatial and temporal pattern of the sulfate aerosol forcing, in conjunction with observed spatial and temporal patterns of temperature trend, may lead to improved empirical estimates of the sensitivity of temperature to perturbations in radiative forcing.

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